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THE MOTION OF SPOTS CONNECTED WITH SOLAR FLARES AND THE POSSIBLE CHARACTER OF ENERGY EXIT FROM FLARE REGIONS

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Photographs of the sun in integrated light have been obtained during flares observed in Hα with the AFP-2 and the solar tower telescope, the focus being equal to 12 meters. It is found that:

1) with the appearance and development of flares a shift of the sunspots is observed in the direction to the flare knots;

2) the commencement of flare development and that of spot motion coincide with a precision of ±5 minutes;

3) the spot motion continues for 2 - 3 hours after the termination of the flare in Hα and is probably of a pulsational-translational character. The amplitude of pulsation increases with the importance of the flare. It is shown that:

1) the volume decreases, due to the conversion of magnetic energy to the internal energy of the gas, by a small fraction in comparison to that observed;

2) the mean values of the observed shifts can be explained by the exit of energy (in the form of cosmic rays, plasma and magnetic fields) from the flare region;

3) taking into account [4] it is concluded that during a flare observed in Hα line, the main fraction of energy is carried away by cosmic rays;

4) after the termination of the flare in Hα and till the end of the spot motion, the energy carried away by "cold" plasma and the magnetic field apparently predominates over the energy of cosmic rays emitted at this same time;

5) ionization losses of cosmic rays are sufficient for an energetical explanation of the observed flare emission in Hα and other spectral lines.

In [1] we showed that the "peaks" of magnetic fields and spots in active regions on the sun are displaced during flares. The amount of such displacement varies and often reaches $2 \cdot 10^9$ cm. In addition such motion is directed, as a rule, to one side of the nucleus of the flare. These results present a general picture of the motion of magnetic "peaks" and spots in active regions during a flare.

The recording of magnetic fields in active regions takes about an hour, so that it is impossible to present a detailed picture of motion by means of maps of magnetic fields.

The aim of the present work is to investigate the motion of spots in active regions. For this purpose systematic photography of the sun in integrated light was carried out on the chromospheric-photospheric telescope AFP-2, and also on the solar tower telescope (BST) of 12-meter focal length. A program of systematic photography was proposed with surveys each half-hour in the case of the quiet sun, and at 2-10 minute intervals at the appearance of a flare; surveys were continued at the same rate for 2-3 hours after the end of the flare. (For the flare of importance 2+ on 30.VIII 1960, the first photograph was taken before the flare and the subsequent series was begun

after its maximum H_α brightness.) Simultaneously the flare was patrolled in H_α on the KG-1 or the AFP-2. By such a program we obtained material for seven flares of various importance ranging from 1 to 2+.

Here we cite the study of material from only three flares which were situated at such a distance from the central meridian of the sun that the effect of rotation and curvature of the solar surface did not affect the observed displacement of spots during the time of observation of around 3-5 hours. We deal with the importance 1+ flare of 16.VIII 1960, the importance 2+ flare of 30.VIII 1960 and the importance 1 flare of 30.VIII 1960.

For data reduction, enlarged images of sunspot groups were successively compared with sketches obtained before the flare. The comparisons were carried out so that large spots coincided as well as possible (in the comparison it was immediately evident that the largest spots are displaced least of all), and then we marked off successive positions of the rest of the spots relative to their original positions.

In the absence of flares the displacement of spots relative to their original positions was small (up to 4"). During the development of flares the displacement of spots is directed and attains great value. The displacement of spots associated with flares, as a function of time, is given in Fig. 1-3. In each case only one example of the relationship is given, since for other spots it is precisely the same. On these graphs are marked off the commencement (H) and the end (K) of the flare in Moscow time. From Fig. 1 and 3, for which surveys of spots were obtained at the very beginning of the development of the flares observed in H_α, we see that the beginning of motion of the spot and the beginning of the development of the flare coincide with an accuracy up to ±5 minutes. These results are confirmed by the rest of the material.

In addition, from Fig. 1-3 it is apparent that the process of displacement of spots takes place not only during the flare observed in H_α, but also continues for several hours after its end.

At the same time we note the wavy character of the curves, which seems real to us; the amplitude of these waves increases with the importance of the flare. Actually the curves of Fig. 2 and 3 were obtained from the same photo-heliogram (atmospheric conditions were identical). While the scatter of points on the curve for the importance 1 flare (Fig. 3) is nearly nonexistent, for the importance 2+ flare (Fig. 2) the scatter is rather substantial. Additional graphically plotted curves of displacement for all spots (Fig. 4) associated with the 2+ flare (30.VIII 1960) show that the wavy character of all curves is roughly the same. For verification of this fact independent control measurements* were carried out which confirmed the results obtained. On Fig. 5 are given curves averaged for all spots. From what has been said it follows that the process of displacement of spots on the surface of the disk probably has a pulsational-transitional character which is maintained throughout all motion.

As was noted in [1], the process of spot convergence during a flare probably takes place through conversion of magnetic energy into gaseous energy, and the consequent escape of energy from the flare region. On the basis of these assumptions, and making use of the observed average spot motion, we can calculate the rate of conversion of magnetic energy into gaseous energy, and the emergent energy flux. Each of these effects will be examined separately.

* The author thanks T. T. Tsap for carrying out the control measurements.

FIG. 1. Motion of a spot associated with importance 1.5 flare, 16.VIII 1960. Beginning of flare - 14^h18^m, end of flare 15^h02^m.

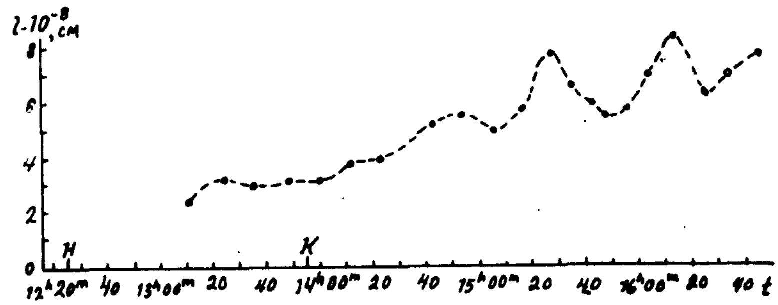

FIG. 2. Motion of a spot associated with importance 2+ flare, 30.VIII 1960. Beginning of flare - 12^h25^m, end of flare - 13^h55^m.

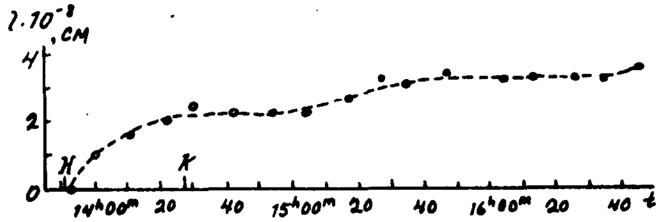

FIG. 3. Motion of a spot associated with importance 1 flare, 30.VIII 1960. Beginning of flare - 13^h52^m, end of flare - 14^h27^m.

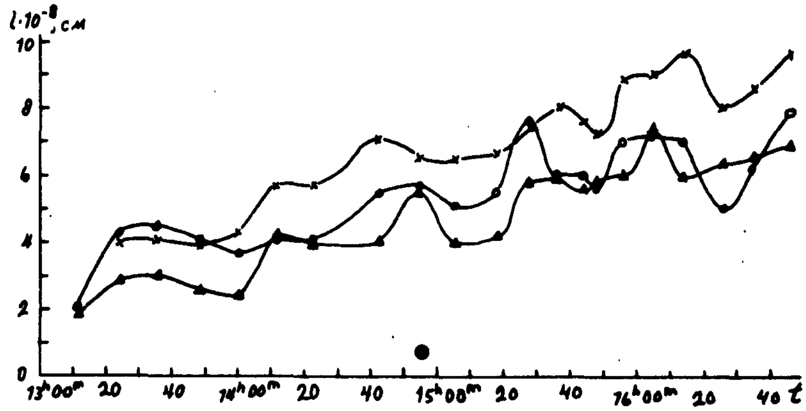

FIG. 4. Motion of spots associated with importance 2+ flare, 30.VIII, 1960.

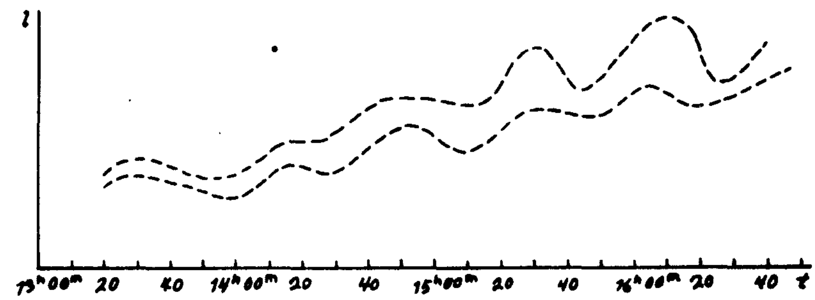

Fig. 5. Averaged curves for all spots (7 spots) for importance 2+ flare, 30.VIII 1960. Upper - author's curve, lower - T. T. Tsap's curve; arbitrary ordinate axis.

1. CONVERSION OF MAGNETIC ENERGY TO INTERNAL ENERGY OF GAS

We will take a conducting medium with magnetic fields. We will examine some isolated volume Q, which is found in equilibrium with the surrounding infinite medium. We assume that at a moment of time $t > 0$, the process of conversion of magnetic energy into internal energy of gas begins, so that the energy does not escape from the volume. In this case the volume will be compressed by external pressure [1]. In order to ascertain the velocity and amount of compression of such an isolated system we use the law of conservation of energy in a magnetized medium, neglecting viscosity and heat-conductivity [2].

We will consider that motion of the medium, diffusion of the magnetic field, and current are perpendicular everywhere to the magnetic field. In this case according to [3], the diffusion term entering into the equation of the law of conservation of energy takes the form $\frac{H^2}{4\pi} D$, where H is the magnetic field strength and D is the displacement velocity of lines of force relative to the medium. We introduce the designation $D = yV$ (y is some function of conductivity, V is the velocity of the medium). If $y = 0$, the displacement velocity of lines of force relative to the medium is equal to zero. This signifies total "freezing-in." But if $y = 1$ then the displacement velocity of lines of force relative to the medium is equal to the transport velocity of the medium. This case actually corresponds to the absence of "freezing-in." Later on we will see (3) that where $y = 1$ the influence of magnetic fields plays no role, i.e., the total pressure is equal only to the gaseous pressure. Taking into account the previous assumption, ignoring the density of kinetic energy, and averaging the total internal energy according to volume, we write down the law of conservation of energy in the form of the first principle of thermodynamics:

$$\frac{dU}{dt} + \frac{dA}{dt} = 0; \tag{1}$$

here U is the total internal energy of volume Q, A is the stress exerted on the volume by the external force, so that

$$U = \left(\varepsilon + \frac{H^2}{8\pi}\right)Q, \tag{2}$$

ε is the density of the internal energy of gas and $\frac{H^2}{8\pi}$ is the density of magnetic energy.

Since the process of compression takes place at constant total pressure, then

$$\frac{dA}{dt} = P_0^*\frac{dQ}{dt} = \left[P_\Gamma + \frac{H^2}{8\pi}(1 - y)\right]\frac{dQ}{dt}, \tag{3}$$

where $P_0^* = P_\Gamma + \frac{H^2}{8\pi}(1 - y)$ is the total pressure, P_Γ is the gas pressure, $(1 - y)\cdot H^2/8\pi$ is the magnetic pressure. For the sake of simplicity we use y = const. Each of the pressure components within the volume P_Γ and $\frac{H^2}{8\pi}$ changes, and value P_0^* is constant. Substituting (2) and (3) in (1) and designating $H^2/8\pi P_0^* = x(t)$, and also considering the volume as cylindrical, after simple transformation we obtain

$$\frac{dx(t)}{dt} = 2\left[\frac{\gamma}{2 - \gamma - y} - x(t)\right]\frac{1}{r(t)}\frac{dr(t)}{dt}, \tag{4}$$

where r(t) is the radius of the cylindrical volume at an arbitrary moment of

time, and $\gamma = \frac{c_p}{c_v} = {}^5/_3$. Formula (4) gives the rate of change of the volume with respect to the velocity of decrease of magnetic field. Actually it is rather difficult to use this formula. More convenient is the integral of formula (4) which can be written in the following form:

$$x(t) = \frac{\gamma}{2 - \gamma - y} - \left[\frac{\gamma}{2 - \gamma - y} - x(t_0)\right] \frac{r^2(t_0)}{r^2(t)} . \tag{5}$$

From (5) it is easy to determine the change in radius of the cylinder

$$\Delta r = r_0 \left[\sqrt{\frac{\frac{\gamma}{2 - \gamma - y} - x(t_0)}{\frac{\gamma}{2 - \gamma - y} - x(t)}} - 1 \right] . \tag{6}$$

Formula (6) gives the change in radius of the cylinder r with respect to the initial relative magnetic pressure $x(t_0)$ and its final value $x(t)$. From this equation it follows that $x(t)$ can change from 1 to 0.

Since always in our case $x(t) < x(t_0)$, from formula (6) we see that where $\gamma + y < 2$ the volume diminishes. In the case of $\gamma + y = 2$ the volume remains constant, and where $\gamma + y > 2$ even increases. This is easy to understand if we keep in mind that y characterizes the extent of interaction of the magnetic field with the medium. Where y is tending toward unity the interaction of the magnetic field with the medium vanishes and the equilibrium of the volume with the medium is fulfilled by gas pressure; but the change in magnetic energy causes an increase in the gas pressure within the volume, from which expansion results. However in partially ionized media y is considerably less than unity, and hence the volume will always contract.

In the limiting case, when $x(t_0) = 1.0$ and $y = 0$ (at the initial moment, magnetic pressure is very great in comparison with gas pressure), and $x(t) = 0$ (after full conversion of magnetic energy), $\Delta r = -0.1\ r_0$. Substituting $r_0 = 2 \cdot 10^9$ cm for the importance 1+ flare of 16.VIII 1960, and using the graph (see Fig. 1), we see that the time of conversion of magnetic energy into gaseous energy, necessary to produce the observed convergence of spots, is equal to 9 minutes at best, and rather strongly depnds on $x\ (t_0)$. After 9 minutes the magnetic fields should disappear in a cylinder of radius $r_0 = 2 \cdot 10^9$ cm and height $h = 5 \cdot 10^8$ cm. The magnetic energy in this cylinder where $H = 500$ gs is on the order of $6 \cdot 10^{31}$ erg. Subsequently we will see that the energy of this flare is on the order of $3 \cdot 10^{31}$ erg. Consequently $x(t)$ must be equal to 0.5. Substituting $x(t) = 0.5$ in (6), and assuming, in the limiting case, that $x(t_0) = 1$, we find that $\Delta r = -0.06\ r_0 = -10^8$ cm. The difference of y from 0 still further decreases Δr, so that $|\Delta r| < 10^8$cm. The time of conversion of magnetic fields in this case will be less than 4 minutes.

Thus we see that due to the conversion of magnetic fields the volume decreases by a small amount in comparison to that observed (observed value is on the order of $8 \cdot 10^8$ cm (see Fig. 1)). In addition, the displacement of spots proceeds during the course of several hours. All of this indicates that during a flare there exists another reason for the convergence of spots. We consider the escape of energy from the region of the flare such a reason. Thus the escape of energy must be decisive in the convergence of spots, and the role of conversion of energy must be negligible.

§2. ESCAPE OF ENERGY FROM THE VOLUME

We will consider only the escape of energy from the volume, without conversion. Imagine a cylindrical volume Q, from which energy escapes only through one cross-section. (The lateral surface and lower section are opaque.) This is a reasonable model of a flare. As the energy escapes from the cylinder the pressure within it drops. The constant external pressure thus causes compression of the cylinder. From the speed of compression of the cylinder we can determine the energy flux through the cross-section.

To do this we designate by W the change in total energy in volume Q, limited by the contracting surface Σ. We designate by w the density of energy in the volume under consideration, so that the law of conservation of energy for such a cylinder will be written in the form

$$\frac{dW}{dt} = \frac{d}{dt}\int_Q w\, dq = \int_S (k\ ds), \tag{7}$$

where k is the flux of energy through the surface S.

Since there is no flow of energy through the lateral surface,

$$\frac{d}{dt}\int_Q w\, dq = -\int_\Sigma P_0^* v_{n\sigma} d\sigma, \tag{8}$$

where P_0^* is the total pressure and $v_{n\sigma}$ is the velocity of displacement of the surface in the direction of the radius.

Having substituted (8) in equation (7) we obtain

$$-\int_\Sigma P_0^* v_{n\sigma} d\sigma = \int_S k ds. \tag{9}$$

Formula (9) describes the process of convergence of spots associated with flares, since the role of conversion of magnetic energy is slight.

We determine the total energy escaping during the whole process in the following manner:

$$W = W_1 + W_2 = \int_0^{t_1}\int_S k_1 ds\ dt + \int_{t_1}^{t_2}\int_S k_2 ds\ dt. \tag{10}$$

Here, in the first integral, the integration according to time includes all of the flare (from beginning to end) observed in Hα, and the second integration covers the period from the end of the flare observed in Hα to the end of motion. In such a presentation the first integral gives the amount of energy escaping during the flare observed in Hα, and the second - the amount of energy emerging from the flare region after its disappearance.

From equation (9) and Fig. 1 we find the average density of flow of energy during the flare is

$$k_1 = \frac{2P_0^* v_{n\sigma} h}{r} = \frac{2\cdot 10^4 \cdot 2\cdot 10^5 \cdot 5\cdot 10^8}{2\cdot 10^9} = 10^9 \ \frac{\text{erg}}{\text{cm}^2\ \text{sec}}$$

and after its ending

$$k_2 = \frac{2P_0^* v_{no} h}{r} = \frac{2\cdot 10^4\cdot 6\cdot 10^4\cdot 5\cdot 10^8}{2\cdot 10^9} = 3\cdot 10^8 \quad \frac{\text{erg}}{\text{cm}^2\ \text{sec}}.$$

Having substituted value k_1 in the first integral of formula (10) we find the order of the amount of energy escaping during the flare observed in Hα:

$$W_1 = Sk_1t_1 = \pi r^2 k_1 t_1 = 3\cdot 10^{31}\ \text{erg},\ t_1 = 2.8\cdot 10^3\ \text{sec}.$$

Similarly, the amount of energy lost after the flare is equal to:

$$W_2 = Sk_2(t_2 - t_1) = 3\cdot 10^{31}\ \text{erg},\ t_2 - t_1 = 9.3\cdot 10^3\ \text{sec}.$$

Taking into account [4], we can consider that the basic portions of the energy during the flare give off cosmic rays. We determine the density and total number of particles. The density of the energy flux of cosmic rays is equal to $k_1 = mV^2n = 10^9\ \frac{\text{erg}}{\text{cm}^2\ \text{sec}}$. Since

$$V = 10^{10}\ \text{cm/sec, and } m = 10^{-24}\ \text{g, then } n \sim 10^3\ \text{cm}^{-3}.$$

This value agrees rather well with the results in [5]. The total number of particles

$$N \sim nSVt_1 = 10^3\cdot 3.4\cdot 10^{18}\cdot 10^{10}\cdot 2.8\cdot 10^3 = 3\cdot 10^{35}.$$

We find the amount of ionization loss of cosmic particles. According to [6] the ionization loss of one proton in each hydrogen line is equal to

$$-\frac{dE}{dx} = \frac{2\pi r_e^2}{\beta^2} m_e c^2 n_a \left[\ln \frac{4m_e^2c^4\beta^4}{(1-\beta^2)^2 I^2(z)} - 2\beta^2\right], \qquad (11)$$

where the ionization potential of hydrogen $I(z) = 13.5$ ev, r_e and m_e are the classic radius and mass of electrons respectively, n_a is the number of hydrogen atoms per unit volume, and β is the ratio of velocity of transient particles to the speed of light c (in our case $V = \frac{1}{3}c$).

If the hydrogen is completely ionized, in (11) n_a must be replaced by n_e (the number of electrons per unit volume), and $I(z)$ by $\hbar\omega_0 = \hbar\sqrt{\frac{4\pi e^2 n_e}{m_e}}$, where $\hbar$ is a Planck constant divided by 2π, and e is the electron charge. The other values have the same meaning as before.

Since for $H = 100$ gauss the radius of gyration of particles with velocity of $V = \frac{1}{3}c$ is equal to 10^4 cm, the particles must be retarded by magnetic fields.

Turning to the loss in units of time and substituting numerical values we obtain

$$-\frac{dE}{dt} = 3.3\cdot 10^{-6} \quad \frac{\text{erg}}{\text{sec}\cdot\text{particle}} \qquad (12)$$

where the average number of particles $n_a = 5\cdot 10^{12}\ \text{cm}^{-3}$. The ionization loss of all particles in units of time is equal to

$$-\frac{dE}{dt} N = 3.3\cdot 10^{-6}\cdot 3\cdot 10^{35} = 10^{30}\ \frac{\text{erg}}{\text{sec}}.$$

We see that the ionization loss is very great. According to the calculations done in [7] the energy emitted by flares (importance 2 or above)

in line $L\alpha$ can be on the order of $5\cdot10^{29}$ erg ($L\alpha$ is the strongest line in this region of the spectrum). X-ray emission of flares is considerably less [8]. In addition, during flares the most intense line in the visible portion of the spectrum is $H\alpha$. Since the ionization loss must ultimately convert into emission, there is sufficient energy to explain the observed emission of flares in $H\alpha$ and other spectral lines.

The second term of formula (11) gives the escape of energy after the flare, i.e., after the heightened emission in $H\alpha$. This escape is probably connected, on the whole, with the escape of "cold" plasma and magnetic fields.

Indeed, by this time the average kinetic energy of electrons must be less than the ionization potential of hydrogen (otherwise there would be strong radiation). Taking into account the great ionization loss of cosmic particles, we can conclude that the density of cosmic rays after the flare fades in $H\alpha$ is considerably less than their density during the period of the flare's radiation in $H\alpha$. In order to obtain a detailed explanation of the character of the escape of cosmic rays from the flare region it is necessary to know which part of the ionization loss becomes radiation in $H\alpha$.*

Preliminary measurements indicate that the region $r_0 = 4\cdot10^9$ cm decreases to roughly $3\cdot10^9$ cm as a result of the approach of "peaks." The intensity of the magnetic field after compression must increase by

$$\frac{\pi r_0^2}{\pi r^2} = \frac{16}{9} = 2 \text{ times.}$$

Such a change in the intensity of the magnetic field should be noticeable. However, records of magnetic fields show that after the convergence of spots the intensity of a magnetic field does not increase [1]. Consequently, the escape of energy in the second stage is connected, on the whole, with the escape of "cold" plasma and with magnetic fields.

After a flare, the flocculi have different structure and their brightness diminishes gradually and very slowly [9]. The brightness of the flocculi could be sustained owing to the ionization loss of cosmic rays possibly present in the volume.

Thus, in resumé, we can imagine that the motion of spots is connected with the escape of energy in the form of cosmic rays, plasma and magnetic fields. However, in the first stage, i.e., during the flare observed in $H\alpha$, the main portion of the energy is carried off by cosmic rays, while in the second stage, i.e., after the flare in $H\alpha$ and until the end of motion in spots, the energy carried off by "cold" plasma and magnetic fields apparently predominates over the energy of cosmic rays escaping during this time. In addition, the ionization loss of cosmic rays is sufficiently great to explain the observed emission of flares in $H\alpha$ and in other lines of the spectrum.

In conclusion the author expresses hearty thanks to corresponding-member of the Akad. Nauk SSSR, A. B. Severny for discussion of a number of matters in the present work, and also to V. G. Kuprienko and M. Dzh. Guseinov for help in obtaining the observational material.

*At the present time E. Ye. Dubov is conducting a detailed calculation of the discharge path of energy for the passage of cosmic particles through the chromosphere, and the flare radiation thus arising in the lines and the continuous spectrum.

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* Electrodynamics of a continuous medium.
** Magneto-hydrodynamics.
*** High-energy particles.